United States
Department of
Agriculture

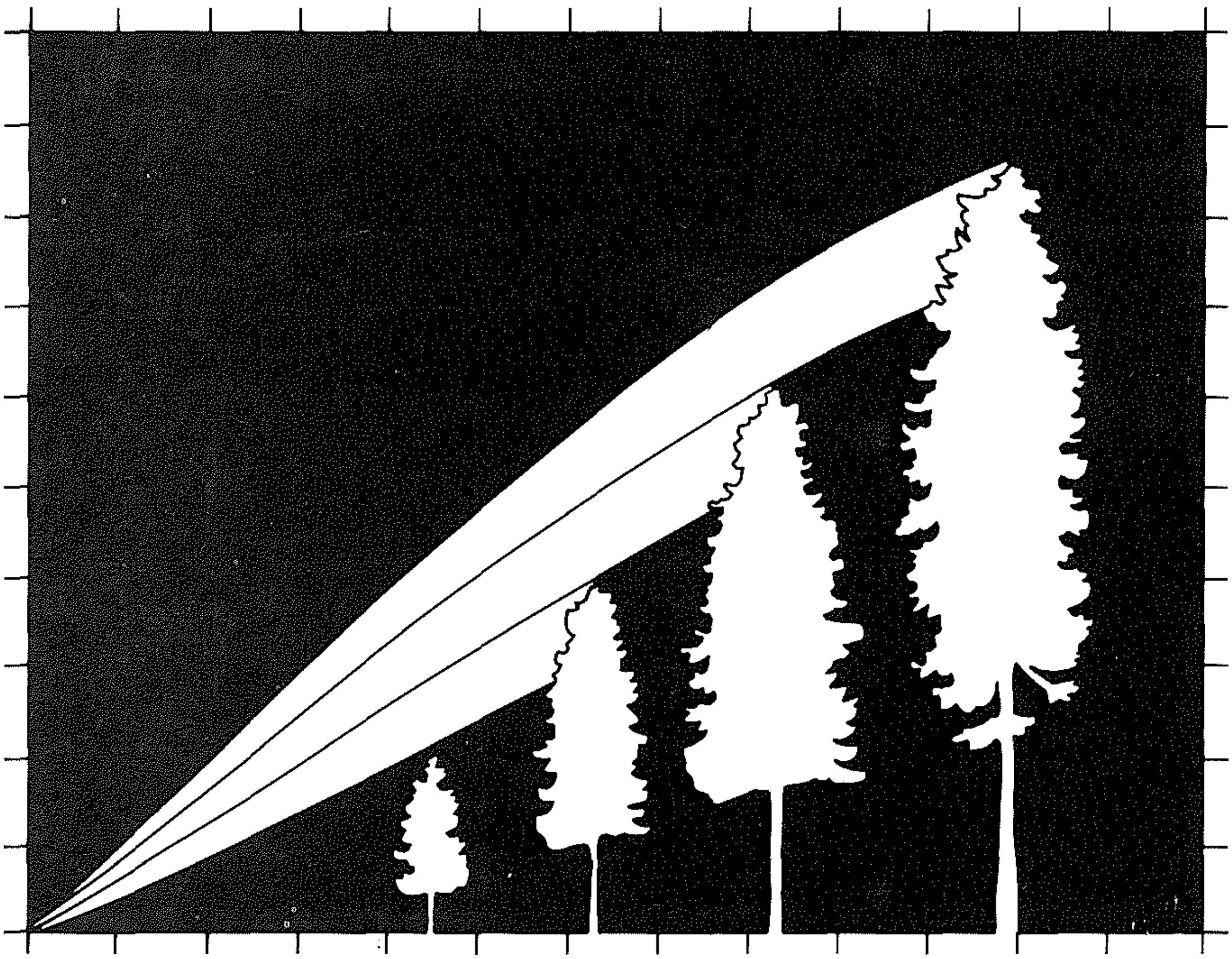
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-185

Site Index Curves for Young-Growth California White Fir on the Western Slopes of the Sierra Nevada

K. Leroy Dolph



The Author:

K. LEROY DOLPH, a research forester assigned to the Station's Silviculture of California Conifer Types Research Unit in Redding, Calif., received a bachelor of science degree (1969) in forest management and a master of science degree (1971) in forest ecology from Colorado State University. He joined the Station in 1977.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

February 1987

Site Index Curves for Young-Growth California White Fir on the Western Slopes of the Sierra Nevada

K. Leroy Dolph

CONTENTS

IN BRIEF. . . .

Dolph, K. Leroy. **Site index curves for young-growth California white fir on the western slopes of the Sierra Nevada.** Res. Paper PSW-185. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1987. 9 p.

Retrieval Terms: site index, increment (height), stem analysis, white fir, *Abies concolor*, Sierra Nevada, California

The lack of growth and yield information and the increasing importance of young-growth California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.) have created a need for methods of estimating the relative potential productivity of forested land areas for this species. Site index, which provides estimates of relative site potentials for a given species by the relationship of tree height to age, is a proven and practical means of estimating this productivity.

Site index curves and equations for young-growth California white fir were developed from stem analyses of 77 trees growing in mixed-conifer stands on the western slope of the Sierra Nevada in California. Site index reference age is 50 years at breast height.

The curves were based on dominant and codominant trees which showed no evidence of past suppression, no visible insect or disease damage, and no broken or deformed tops. If more than one tree on a site is suitable for site index estimation, age at breast height and total height should be measured and a site index calculated using each tree. The highest site index obtained should be considered the site index for that particular area.

Site index curves at 10-foot intervals for breast-height ages of 10 to 80 years are presented for approximate field estimates of site index. For more precise estimates, regression coefficients for each year and the site index estimating equation are given.

INTRODUCTION

Site index—the height of a specified stand component at a chosen reference age (Spurr 1952)—is often used to estimate the potential productivity of a forested site. This estimate of potential productivity is basic to the prediction of yields and the determination of optimum stocking levels. Indeed, site index is an important independent variable in the internal prediction equations of many stand growth projection systems.

A geographic variant of the Stand Prognosis Model (Stage 1973) is being developed by this Research Unit for young-growth mixed-conifer stands on the western slopes of the Sierra Nevada. Species-specific site index was found to be a useful predictor of basal area increment for this variant. Since suitable site curves for young-growth stands were not available for all species of the mixed-conifer type, three site index estimating equations were developed. Site index curves for incense-cedar (*Libocedrus decurrens* Torr.) (Dolph 1983), California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*) were produced from these equations.

Three key considerations guided the development of the site index estimating equations and associated site curves:

- A reference age of 50 years was used. Because of the young-growth aspect of the study, reference ages of 100 years or more would be beyond ages actually encountered.
- Breast-height age, rather than total age, was used. Breast-height age is not only more convenient to use but also represents a height when most species have passed the period of establishment. It also eliminates the necessity of adding a flat correction factor to obtain total age (Husch 1956).
- The curves are based solely on data collected from the western slopes of the Sierra Nevada. The western Sierra is recognized as distinct, characterized by (among other features) its unique geologic structure and relatively high winter precipitation.

Site curves currently available for California white fir were developed by Schumacher (1926), Dunning and Reineke (1933), and Biging and Wensel (1984). Schumacher's, and Dunning and Reineke's curves were constructed by using the harmonic guide curve method. Curves developed by this older method have several problems. Since they are based only on tree height and age measurements at one time, site index was not observed or measured directly but inferred from the guide curve. Another weakness of proportional curves based on one master guide curve is that they have an anamorphic pattern of height growth, i.e., the curves have the same shape at all levels of site index.

Stem analysis methods have largely eliminated these problems (Monserud 1984) for two reasons:

- Site index is observed rather than inferred;
- Polymorphic curves (which do not have the same shape or trend for each site classification) can be modeled adequately, since height growth patterns for each tree are known.

Biging and Wensel's curves for northern California mixed-conifers were developed using stem analysis techniques. However, their curves were developed from combined data of six mixed-conifer species, not specifically for white fir. Only 36 percent of their sample trees were white fir, and only a portion of these were from the Sierra Nevada.

Intensive timber management requires the most accurate and adequate site index estimates available for a specific area and tree species. However, confusion may occur if foresters must choose between several sets of site curves. They may be uncertain about how applicable each set may be to specific conditions of their local area. Therefore, the objectives of this paper are threefold:

- To provide a method for precise site index estimates of young-growth California white fir in the Sierra Nevada
- To compare these estimates with other published site index curves
- To make recommendations for use of site index curves for young-growth species of the Sierra Nevada.

This paper describes site index curves for young-growth California white fir that express site index in terms of total height of dominant and codominant trees at 50 years breast-height age. The curves are based on and specifically intended for young-growth white fir on the western slopes of the Sierra Nevada.

METHODS

Stand and Sample Tree Characteristics

Young-growth natural stands which fit the definition of Sierra Nevada Mixed Conifer Type (Tappeiner 1980) were randomly sampled throughout the western slopes of the Sierra Nevada (*fig. 1*). Young-growth stands were defined as those in which more than 75 percent of the trees were less than

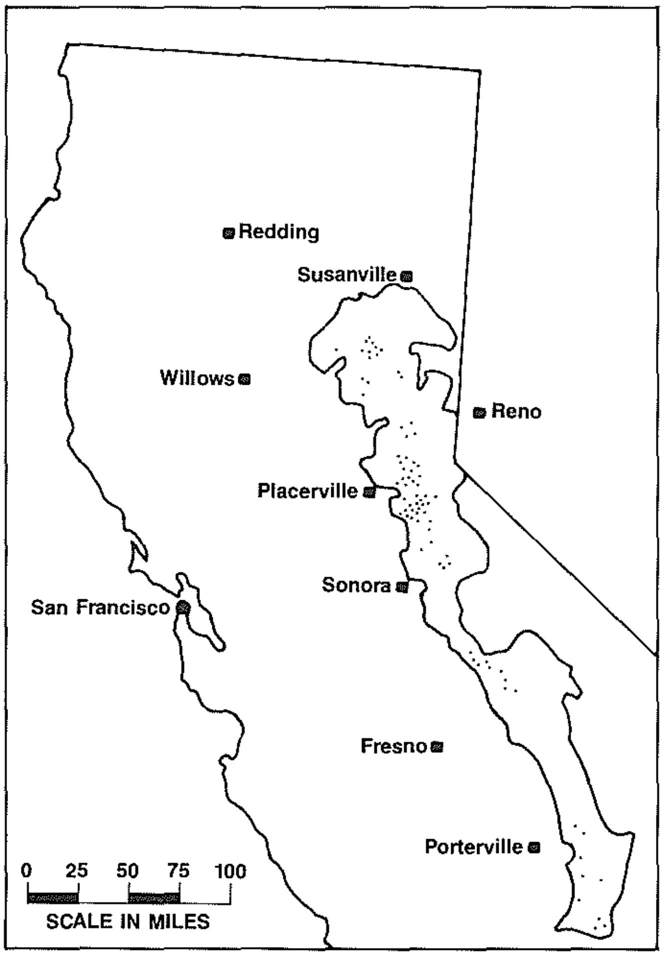


Figure 1—Location of study area and distribution of sample trees used in construction of site index curves for young-growth California white fir. The study area is defined by the boundaries of the six National Forests on the western slopes of the Sierra Nevada.

or equal to 80 years old at breast height (b.h.). Plots were variable-radius prism plots using wedge prisms with basal area factors of 10, 20, 40, or 60, depending upon stand characteristics. Most mixed-conifer stands are uneven-aged by definition; however, they are typically composed of even-aged groups. At each sample plot, one main age class could be identified and, except for occasional trees, maximum age differences were generally 10 to 20 years.

At each sample point, from 4 to 10 randomly selected trees were felled and sectioned for collection of stem analysis data. All mixed-conifer species were sampled in proportion to their abundance at each sample site. Stems were analyzed on 412 white fir trees throughout the study area. However, since all trees were selected randomly, only a portion of these were suitable for preparing the site index curves. Suitable site trees had the following characteristics:

- No visible infection of disease or insects.
- No broken or deformed tops currently visible or apparent in the past from plotting of the stem analysis data.
- Crown ratio of at least 40 percent. Lower crown ratios may indicate slower height growth resulting from intense intertree competition.
- Age at breast height of at least 50 years but not greater than 80 years.
- Dominant or codominant crown position for their entire lives (no evidence from stem analysis of past suppression of either diameter or height growth).

Data Collection

Stem analysis data from white fir trees which met the above criteria were collected at 77 sample locations. When more than one suitable tree was found at a location, the tallest tree for its breast-high age was used for the analysis. Each tree was marked at breast height (4.5 ft [1.4 m] aboveground on the uphill side of the tree) before felling. All subsequent height measurements were taken from this reference point. Height to the tip of the tree was first recorded. Height of the tree when growth started 10 years ago was next determined by counting branch whorls and cutting cross-sections down the stem until the lowest section that contained 10 complete growth rings was found. Height to this section was then recorded. This procedure was repeated for the 20-year section. Ring counts were made at additional cross-sections taken at breast height, 5.25 and 10.5 ft (1.6 and 3.2 m) above breast height, and at 18.5-ft (5.6 m) intervals up the stem to the 20-year section.

Height/Age Curves

The breast-height age of each tree when its height had reached each sectioning point was determined by subtracting the ring count at each respective section from the present breast-height age. The height above b.h. of each section was plotted over b.h. age for each of the 77 trees. The points for each tree were connected with hand-drawn smooth curves. Heights were read from these curves for b.h. ages 10 to 75 years at 5-yr intervals of b.h. age. These heights and ages were used in the subsequent analysis. Heights for ages over 75 years were eliminated from further analysis because the older age classes were inadequately represented. From this point, the methods outlined by Barrett (1978) and Cochran (1979) were used for the site index curve construction.

CONSTRUCTION OF SITE INDEX CURVES

Site index estimation curves of the form

Site index = f (height, age)

can be developed from stem analysis data, since an estimate of site index is available in the form of measured heights of the

Table 1—*Statistics for separate regressions of SI - 4.5 = a_0 + b_0 (HT - 4.5) for each indicated age of the sample trees*

Breast-high age (yrs)	a_0	b_0	r^2	Standard error of estimate (ft)	Total observations
10	41.801	3.3021	0.3014	15.822	77
15	32.799	2.5402	.4917	13.496	77
20	26.152	1.9802	.6539	11.136	77
25	20.391	1.6244	.7575	9.322	77
30	14.889	1.4122	.8472	7.400	77
35	9.524	1.2666	.9218	5.294	77
40	5.677	1.1530	.9680	3.389	77
45	2.699	1.0622	.9926	1.626	77
50	0	1	1	0	77
55	-2.510	.9545	.9939	1.564	68
60	-4.890	.9205	.9817	2.744	56
65	-5.271	.8739	.9573	3.930	43
70	-6.741	.8497	.9378	4.124	29
75	-5.270	.7833	.9177	4.664	17

sample trees at the chosen reference age, in addition to heights at other ages (Curtis and others 1974). For a specified age, therefore,

$$\text{Site index} = f\,(\text{height}).$$

Total height at b.h. age 50 was arbitrarily called the site index for each tree. A linear regression line was then calculated for the relationship of site index to height for each 5-year interval starting with 10 years and ending with 75 years (*table 1*). There was no indication from plotting the data that anything other than a straight line would have been appropriate for each age. The basic equation for these regressions is

$$SI - 4.5\text{ ft} = a_0 + b_0(HT - 4.5\text{ ft}) \qquad (1)$$

in which

SI = site index in feet,
HT = total height in feet,
a_0 and b_0 = regression parameters estimated by least squares.

Subtracting 4.5 feet provided a common origin at b.h. for the height, age, and site index scales.

The b_0 coefficients for the 14 regressions, which express the relationship of site index to height at each age interval, were then plotted over age, and a smooth progression of b_0 values resulted *(fig. 2)*. Nonlinear regression was used to fit a smooth curve to the plotted points. The estimates of b_0 were smoothed over age by the equation

$$\hat{b}_0 = 38.020235(\text{age}^{-1.052133})(e^{(0.009557)(\text{age})})$$

This equation was conditioned to pass through 1.00 at breast-high age 50.

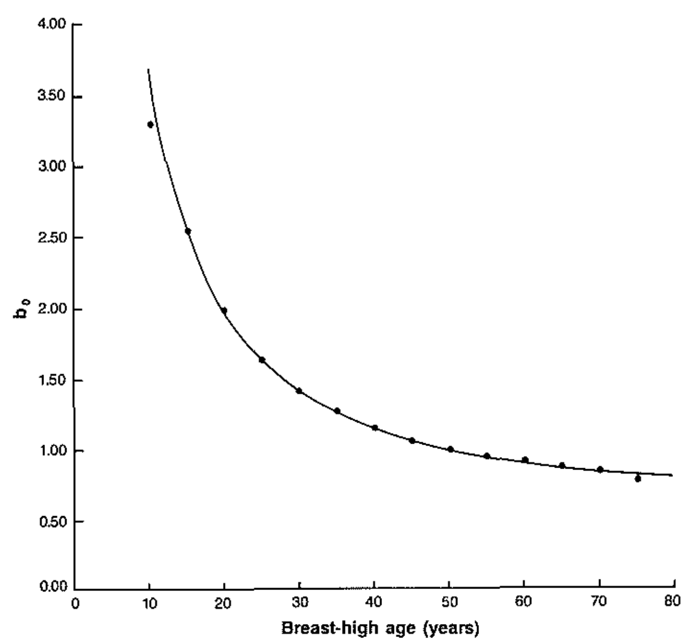


Figure 2—b_0 values in equation SI − 4.5 ft = a_0 + b_0(HT − 4.5 ft) as a function of age. Plotted points are actual b_0 values. Solid line is curve expressed by the equation

$$\hat{b}_0 = 38.020235(\text{age}^{-1.052133})(e^{(0.009557)(\text{age})})$$

Standard error of estimate is 0.1099 and r^2 equals 0.9760.

Table 2—*Statistics for separate regressions of HT - 4.5 = $a_i + b_i(SI - 4.5)$ for each indicated age; adjusted HT - 4.5 = $a_i + b_i(65.41)$*

Breast-high age (yrs)	a_i	b_i	r^2	Standard error of estimate (ft)	Total trees	Adjusted average HT - 4.5 (ft)
10	1.1785	0.0913	0.3014	2.6307	77	7.15
15	0.1761	.1936	.4917	3.7257	77	12.84
20	-1.7757	.3302	.6539	4.5478	77	19.83
25	-2.7899	.4664	.7575	4.9947	77	27.71
30	-3.4659	.5999	.8472	4.8230	77	35.77
35	-3.4811	.7278	.9218	4.0128	77	44.12
40	-3.1055	.8395	.9680	2.8920	77	51.81
45	-2.0868	.9345	.9926	1.5251	77	59.04
50	0	1	1	0	77	65.41
55	3.0513	1.0412	.9939	1.6330	68	71.16
60	6.6123	1.0665	.9817	2.9533	56	76.37
65	9.2141	1.0955	.9573	4.3998	43	80.87
70	12.3050	1.1037	.9378	4.7005	29	84.50
75	12.5041	1.1717	.9177	5.7043	17	89.14

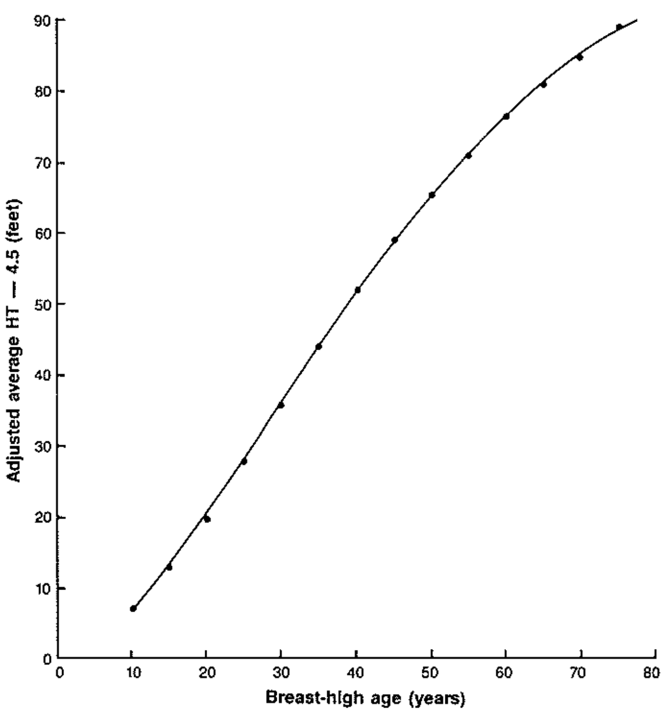


Figure 3—Average height as a function of age. Plotted points are average heights - 4.5 feet. Solid line is curve expressed by the equation

$$\hat{\overline{HT}} - 4.5\text{ ft} = 101.842894(1 - e^{(-0.001442)(age^{1.679259})})$$

Standard error of estimate is 0.3381 and r^2 equals 0.9998.

A curve of average height as a function of b.h. age was constructed next. Individual regressions for each 5-year interval of age, which express height as a function of site index *(table 2)*, were made using the equation

$$HT - 4.5\text{ ft} = a_i + b_i(SI - 4.5\text{ ft}) \quad (2)$$

At ages beyond 50 years, the sample became progressively smaller and mean site index was slightly different. Average heights for these older ages were adjusted to the mean overall site index using the a_i and b_i values of the individual regressions by the equation

$$\overline{HT} - 4.5\text{ ft} = a_i + b_i(\overline{SI} - 4.5\text{ ft})$$

in which $\overline{HT}$ equals adjusted average height, and the mean overall site index of the 77 samples ($\overline{SI}$) equals 69.91 ft. $\overline{HT}$ - 4.5 ft was then plotted over age for each 5-year interval. Estimates of $\overline{HT}$ were smoothed over age by the equation

$$\hat{\overline{HT}} - 4.5\text{ ft} = 101.842894(1 - e^{(-0.001442)(age^{1.679259})})$$

in which $\hat{\overline{HT}}$ is the estimate of adjusted average height *(fig. 3)*. This equation was conditioned to pass through mean site index ($\overline{SI}$) 69.91 (- 4.5 ft) at breast-high age 50. $\hat{\overline{HT}}$ and $\hat{b}_0$ values for each year were then used to calculate the corresponding intercept a_0, where

$$\hat{a}_0 = (\overline{SI} - 4.5\text{ ft}) - \hat{b}_0(\hat{\overline{HT}} - 4.5\text{ ft}).$$

The values for $\hat{a}_0$ and $\hat{b}_0$ are given for each year *(table 3)*.

Table 3—*Values for $\hat{a}_0$ and $\hat{b}_0$ by years for estimating site index for young-growth California white fir by the equation $SI - 4.5\,ft = a_0 + b_0 (HT - 4.5\,ft)$*

Breast-high age (yrs)	$\hat{a}_0$	$\hat{b}_0$	Breast-high age (yrs)	$\hat{a}_0$	$\hat{b}_0$	Breast-high age (yrs)	$\hat{a}_0$	$\hat{b}_0$
10	40.2526	3.7101	34	10.8498	1.2877	58	-3.4820	.9234
11	38.6053	3.3883	35	9.9949	1.2610	59	-3.8435	.9156
12	37.0087	3.1216	36	9.1655	1.2359	60	-4.1902	.9082
13	35.4588	2.8970	37	8.3612	1.2124	61	-4.5225	.9011
14	33.9523	2.7055	38	7.5815	1.1901	62	-4.8409	.8944
15	32.4867	2.5402	39	6.8261	1.1692	63	-5.1460	.8879
16	31.0598	2.3962	40	6.0946	1.1494	64	-5.4381	.8817
17	29.6700	2.2698	41	5.3866	1.1306	65	-5.7178	.8757
18	28.3157	2.1578	42	4.7016	1.1129	66	-5.9854	.8701
19	26.9959	2.0581	43	4.0392	1.0961	67	-6.2415	.8646
20	25.7095	1.9687	44	3.3991	1.0802	68	-6.4866	.8594
21	24.4556	1.8881	45	2.7807	1.0651	69	-6.7210	.8545
22	23.2335	1.8152	46	2.1837	1.0507	70	-6.9452	.8497
23	22.0425	1.7489	47	1.6075	1.0371	71	-7.1596	.8452
24	20.8819	1.6883	48	1.0518	1.0241	72	-7.3647	.8408
25	19.7513	1.6329	49	0.5162	1.0118	73	-7.5610	.8366
26	18.6502	1.5819	50	.0000	1.0000	74	-7.7487	.8327
27	17.5780	1.5350	51	-0.4971	.9888	75	-7.9284	.8289
28	16.5344	1.4915	52	-0.9756	.9781	76	-8.1004	.8253
29	15.5189	1.4513	53	-1.4359	.9679	77	-8.2651	.8218
30	14.5311	1.4139	54	-1.8786	.9582	78	-8.4230	.8185
31	13.5707	1.3790	55	-2.3040	.9489	79	-8.5744	.8154
32	12.6373	1.3465	56	-2.7128	.9400	80	-8.7196	.8124
33	11.7304	1.3161	57	-3.1053	.9315			

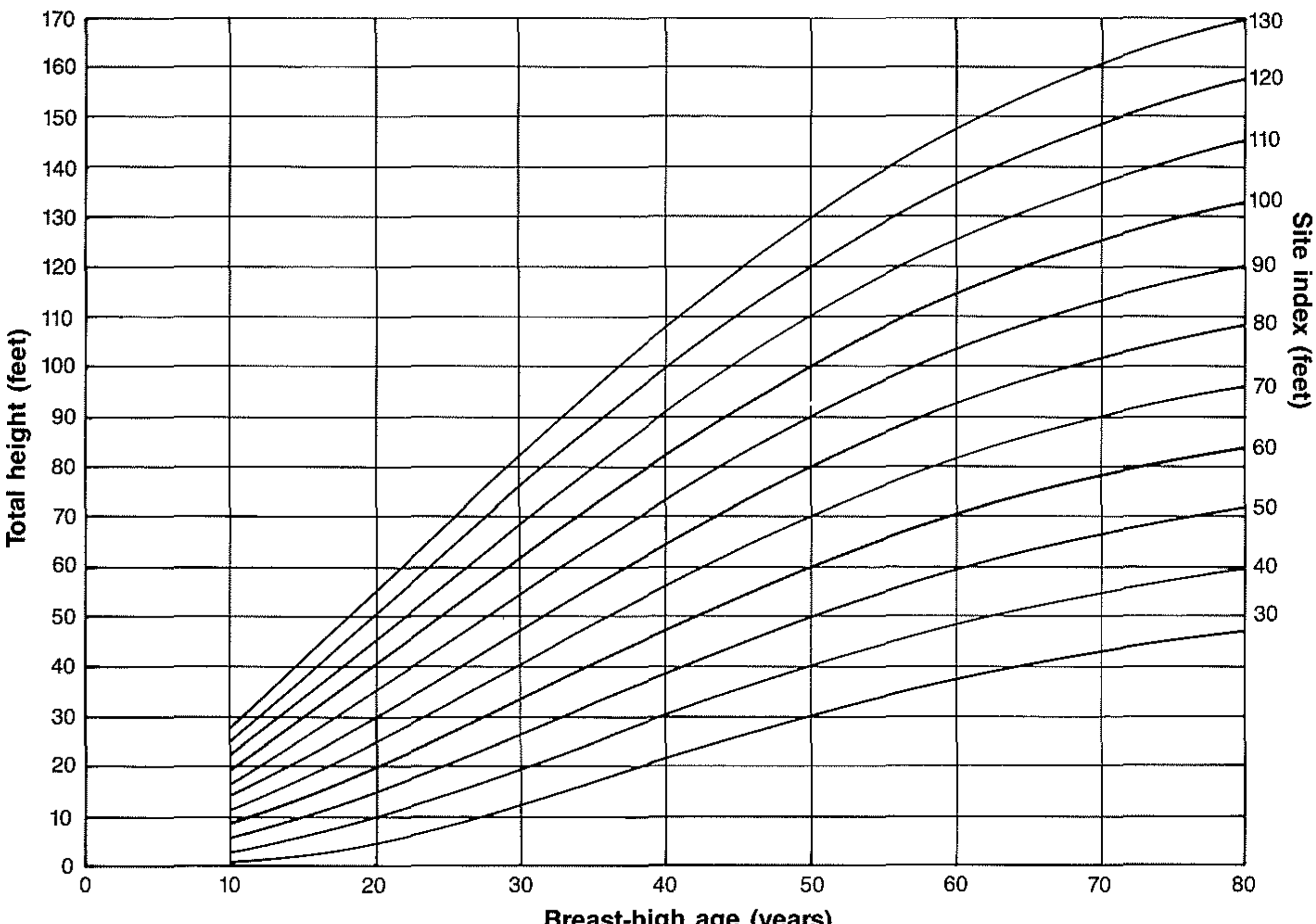


Figure 4—Site index curves for young-growth California white fir on the western slopes of the Sierra Nevada. Base age is 50 years at breast height.

EQUATION FOR ESTIMATING SITE INDEX

Substituting the appropriate expressions for $\hat{a}_0$, $\hat{b}_0$, and $\hat{\bar{HT}}$ in the basic equation

$$SI - 4.5\ ft = a_0 + b_0(HT - 4.5\ ft)$$

gives the final equation to estimate site index as a function of breast-height age and total tree height.

$$\hat{SI} = 69.91 - [38.020235(age^{-1.052133})(e^{(0.009557)(age)})] \cdot [101.842894(1 - e^{(-0.001442)(age^{1.679259})})] + [HT - 4.5] \cdot [38.020235(age^{-1.052133})(e^{(0.009557)(age)})] \quad (3)$$

For approximate estimates of site index, either the curves developed from this equation *(fig. 4)* or the values of total tree height by breast-height age and site index classes *(table 4)* can be used. To obtain precise estimates, the equation

$$SI - 4.5\ ft = a_0 + b_0(HT - 4.5\ ft)$$

can be solved using the appropriate a_0 and b_0 values *(table 3)*. As an example, for a tree 47 years old at breast height and 73 feet in total height, the equation

$$SI - 4.5\ ft = 1.6075 + 1.0371\ (73 - 4.5\ ft)$$

would be solved for a site index estimate of 77.1 ft.

For computer or calculator applications, equation (3) is useful for programming the estimating procedure.

To determine the precision of site index estimates made from equation 3, differences between actual site index (SI) and predicted site index ($\hat{SI}$) were calculated from the heights

Table 4—*Total height of dominant and codominant white fir by breast-height age and site index*

Breast-high age (yrs)	White fir site index (ft)																				
	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130
10				5	6	7	9	10	11	13	14	15	17	18	19	21	22	23	25	26	27
12				6	7	9	10	12	14	15	17	18	20	22	23	25	26	28	30	31	33
14			5	7	9	11	12	14	16	18	20	22	24	25	27	29	31	33	35	36	38
16			6	8	11	13	15	17	19	21	23	25	27	29	31	33	36	38	40	42	44
18		6	8	10	12	15	17	19	22	24	26	29	31	33	36	38	40	43	45	47	50
20		7	9	12	15	17	20	22	25	27	30	32	35	37	40	42	45	48	50	53	55
22	6	9	11	14	17	20	22	25	28	31	33	36	39	42	44	47	50	53	55	58	61
24	7	10	13	16	19	22	25	28	31	34	37	40	43	46	49	52	55	58	61	64	66
26	9	12	15	18	21	25	28	31	34	37	40	44	47	50	53	56	59	63	66	69	72
28	11	14	17	21	24	27	31	34	37	41	44	47	51	54	57	61	64	67	71	74	78
30	12	16	19	23	26	30	33	37	41	44	48	51	55	58	62	65	69	72	76	79	83
32	14	18	21	25	29	33	36	40	44	47	51	55	59	62	66	70	73	77	81	85	88
34	16	20	24	28	31	35	39	43	47	51	55	59	62	66	70	74	78	82	86	90	94
36	18	22	26	30	34	38	42	46	50	54	58	62	66	70	74	78	82	86	91	95	99
38	20	24	28	32	36	41	45	49	53	57	62	66	70	74	78	83	87	91	95	99	104
40	21	26	30	34	39	43	47	52	56	61	65	69	74	78	82	87	91	95	100	104	108
42	23	28	32	37	41	46	50	55	59	64	68	73	77	82	86	91	95	100	104	109	113
44	25	30	34	39	43	48	53	57	62	67	71	76	81	85	90	94	99	104	108	113	118
46	27	31	36	41	46	50	55	60	65	70	74	79	84	89	93	98	103	108	112	117	122
48	28	33	38	43	48	53	58	63	67	72	77	82	87	92	97	102	106	111	116	121	126
50	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130
52	32	37	42	47	52	57	62	67	72	78	83	88	93	98	103	108	113	118	124	129	134
54	33	38	44	49	54	59	64	70	75	80	85	90	96	101	106	111	117	122	127	132	137
56	35	40	45	50	56	61	66	72	77	82	88	93	98	104	109	114	120	125	130	136	141
58	36	41	47	52	58	63	68	74	79	85	90	95	101	106	112	117	123	128	133	139	144
60	37	43	48	54	59	65	70	76	81	87	92	98	103	109	114	120	125	131	136	142	147
62	38	44	50	55	61	66	72	78	83	89	94	100	106	111	117	122	128	133	139	145	150
64	40	45	51	57	62	68	74	79	85	91	96	102	108	113	119	125	130	136	142	147	153
66	41	46	52	58	64	69	75	81	87	92	98	104	110	115	121	127	133	138	144	150	156
68	42	48	53	59	65	71	77	82	88	94	100	106	112	117	123	129	135	141	146	152	158
70	43	49	54	60	66	72	78	84	90	96	102	107	113	119	125	131	137	143	149	154	160
72	44	50	55	61	67	73	79	85	91	97	103	109	115	121	127	133	139	145	151	157	163
74	44	50	56	62	68	74	80	86	92	98	104	110	116	122	128	135	141	147	153	159	165
76	45	51	57	63	69	76	82	88	94	100	106	112	118	124	130	136	142	148	154	160	166
78	46	52	58	64	70	76	83	89	95	101	107	113	119	125	131	138	144	150	156	162	168
80	47	53	59	65	71	77	84	90	96	102	108	114	120	127	133	139	145	151	157	164	170

of each tree at each 5-year age interval (data from the original height-age curve for each tree).

The residual sum of squares at each 5-year interval was calculated by summing the squares of these differences in which

$$\text{residual SS} = (SI - \hat{SI})^2$$

The mean square deviation from regression, SE^2, which is the estimate of the variance of the errors, was calculated by

$$SE^2 = \frac{\text{residual SS}}{n - 2}$$

in which n = the number of observations and 2 = the number of parameters estimated. The standard error of the estimate (SE) is the square root of the variance of the errors.

The estimate of the variance, the standard error of the estimate, and the coefficient of determination (R^2) for each 5-year age interval are only approximate because the $\hat{a}_0$ and $\hat{b}_0$ values for each age are themselves estimated values of a_0 and b_0, predicted with their own degrees of freedom *(table 5)*.

As expected with any set of site index curves, the estimates become more precise as tree age approaches index age. At age 40, for example, 87 percent of the estimates are within 5 feet of actual site index. At age 20, only 25 percent of the estimates are within 5 feet of actual site index.

APPLICATION

The site index curves for California white fir apply to young-growth mixed-conifer stands on the western slopes of the Sierra Nevada. When the forest is composed of recognizable even-aged groups perpetuated by group selection, careful selection of site trees should produce consistent site estimates, comparable to those in even-aged stands (Curtis 1977).

The curves were developed from sample trees on variable radius prism plots. If fixed radius sample plots are used, it is recommended that plots do not exceed 1/5 acre in size. Regardless of plot size, the critical criterion is that all site trees selected at one area be growing on the same site type; that is, the site is homogeneous with respect to stand composition, soil type, slope percent, and aspect.

To determine the site index of a given area, total height and age at breast height must be measured for selected site trees which meet the following specifications:

- Young-growth white fir, at least 10 years but not over 80 years old at breast height.
- Crown position dominant or codominant and appears to have been so throughout the course of its development.
- Visibly free of insects and disease.
- No top damage, no broken or deformed top, such as crooks, scars, or forks.
- Crown ratio at least 40 percent.
- Increment core taken at breast height should not show any fire scars, mechanical damage, or any period of suppression followed by release.

If more than one tree on a site is suitable for site index estimation, calculate the site index for each tree. The highest site index obtained from all sample trees is the best estimate of site index for the area sampled if selection of site trees is random with respect to site quality.

Site indexes calculated with trees with b.h. age greater than 75 years should be used with caution, since such estimates are made with extrapolations of the basic data.

Table 5—*Statistics for precision of site index estimates obtained from equation 3*[1]

Breast-high age (yrs)	Total trees	Variance $(SE)^2$	Standard error of estimate (SE)	Coefficient of determination (R^2)
10	77	253.92	15.93	0.292
15	77	182.25	13.50	.491
20	77	124.49	11.16	.653
25	77	87.07	9.33	.757
30	77	54.85	7.41	.847
35	77	28.08	5.30	.922
40	77	11.54	3.40	.968
45	77	2.71	1.65	.992
50	77	0	0	1
55	68	2.50	1.58	.994
60	56	7.66	2.77	.981
65	43	15.54	3.94	.957
70	29	17.06	4.13	.945
75	17	23.40	4.84	.940

[1] $\hat{SI} = 69.91 - [38.020235(age^{-1.052133})(e^{(0.009557)(age)})] \cdot [101.842894(1 - e^{(-0.001442)(age^{1.679259})})] + [HT - 4.5] \cdot [38.020235(age^{-1.052133})(e^{(0.009557)(age)})]$

CURVE COMPARISON

Biging and Wensel's Curves

The site index curves generated with equation 3 were compared with Biging and Wensel's young-growth mixed-conifer curves *(fig. 5)*. The curves differ substantially both below and above the reference age of 50 years at breast height. At ages below the reference age, differences between the curves depend on site quality. When site index is less than 80, the white fir curves show less height for a given age than the

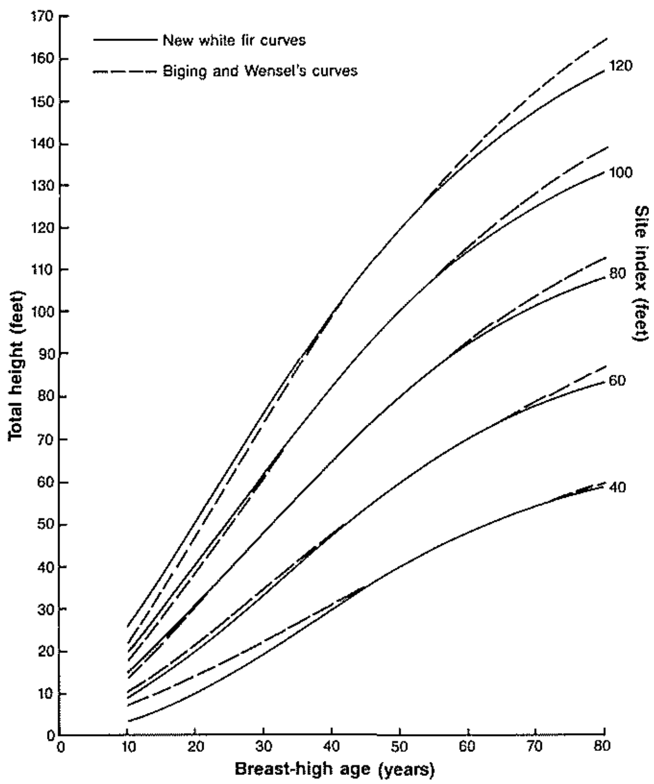


Figure 5—Site index curves for California white fir, with Biging and Wensel's mixed-conifer site curves superimposed.

mixed-conifer curves. As site index increases above 80, the white fir curves show more height for a given age. At ages above the reference age, Biging and Wensel's curves show higher heights for a given age on all sites, with differences in height increasing as site index increases. The curves show that the height-growth rate of white fir begins to decrease earlier than the combined rate for mixed-conifers.

Several factors account for differences between the two sets of curves. Not only were different techniques used in curve construction, but the data in the analyses were quite different. The trees in Biging and Wensel's analysis consisted of six species from four forest types. Only 16 percent of their sample trees were white fir from the mixed-conifer type. Differences in height-growth patterns would be expected among the six species, as evidenced by the earlier levelling off of the white fir curves.

Sampling design is another factor accounting for differences in curve shapes. Biging and Wensel's data came from 38 selectively chosen sites, with a bias in their sample toward higher site qualities. This resulted in a higher average site index for their study (80 feet at 50 years). Data for the white fir curves came from 77 randomly selected sites with an average site index of 70 feet at 50 years breast-height age.

Schumacher's Curves

The site index curves generated with equation 3 also were compared with Schumacher's (1926) site curves for white fir at three levels of site index (*fig. 6*). Since Schumacher's curves are for total age, the conversion factors used by Biging and Wensel (1984) were subtracted to put Schumacher's curves on a breast-height age basis. These factors were 5, 7, and 10 years for the high, medium, and low sites, respectfully. Site index (tree height at 50 years breast-height age) was then determined for the adjusted curves. The three curves used for comparison were high (site index 107), medium (site index 71), and low (site index 31).

Schumacher's curves (*fig. 6*) demonstrate the problem when stem analysis techniques are not used in curve construction. Since no stands under 40 years total age were measured, curve shape below this age was based on total height and age measurements of a few individual trees. The new curves, based on stem analysis data, show completely different height-growth patterns on the medium and high sites. At ages beyond the index age, the new curves show more height for a given age on the low and medium sites and somewhat lower heights for given ages on the high site.

The important feature of both sets of curves for the medium and high sites is the basically same shape beyond the index age. Although these curves show slightly different levels of actual height for a given age, the rates of height growth for ages beyond 50 years are almost identical. Since both sets of curves were developed specifically from white fir data, this supports the inference that white fir height growth levels off earlier than other mixed-conifer species.

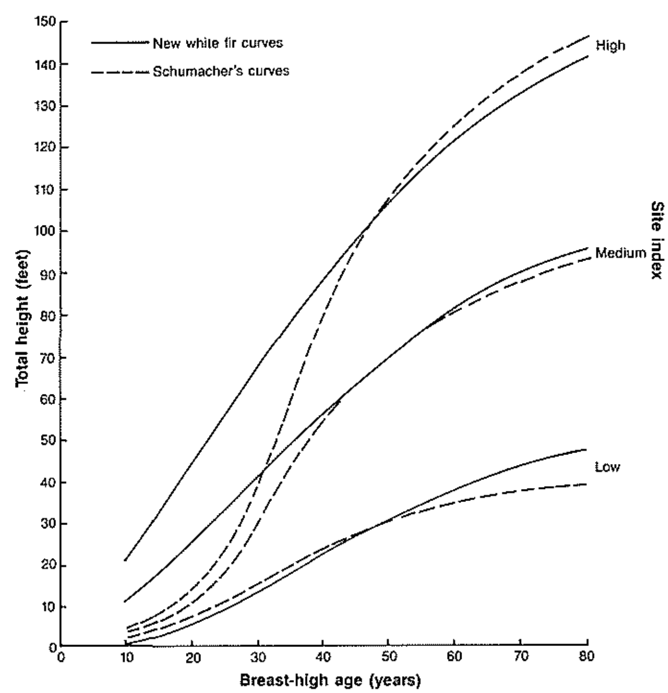


Figure 6—Site index curves for California white fir, with Schumacher's white fir curves superimposed. The three levels of site index are high (site index 107), medium (site index 71), and low (site index 31).

Dunning and Reineke's Curves

Comparisons were not made with Dunning and Reineke's (1933) site curves. In addition to the problem of total age reference, rather than breast-height age, these curves are also based on combined data from a number of species. However, Biging and Wensel (1984) compared their curves with those by Dunning and Reineke. At older ages (beyond age 70), Dunning and Reineke's curves projected even greater heights on the higher sites than Biging and Wensel's mixed-conifer curves.

CONCLUSIONS

The site index curves presented here better reflect actual site potential for white fir within the mixed-conifer type on the western slopes of the Sierra Nevada than Biging and Wensel's mixed-conifer site curves for northern California. Noticeable differences in height growth patterns between white fir and other mixed-conifer species are demonstrated. The new curves are also superior to Schumacher's white fir curves, especially for ages less than 50 years. The use of breast-height age rather than total age also overcomes several problems with site index estimation for white fir.

Site index curves developed from data of a single species give more precise estimates of site potential for that species than curves developed from combined data of several species. Site index curves for incense-cedar (Dolph 1983) and ponderosa pine (Powers and Oliver 1978), which were developed specifically for those species, are recommended for young-growth stands.

Site index curves developed from the combined data of several species can be useful in some situations. For example, when a species or suitable site trees of that species are absent, site index still may be obtained by measuring suitable site trees of other species. Since Biging and Wensel's site index curves for mixed-conifers were constructed from stem analysis data and have a breast-height reference age, they should produce more reliable estimates than Dunning and Reineke's site curves.

REFERENCES

Barrett, James W. **Height growth and site index curves for managed, even-aged stands of ponderosa pine in the Pacific Northwest.** Res. Paper PNW-232. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 14 p.

Biging, Greg S.; Wensel, Lee C. **Site index equations for young-growth mixed conifers of northern California.** Res. Note No. 8. Berkeley: Department of Forestry and Resource Management, University of California; 1984. 13 p.

Cochran, P. H. **Site index and height growth curves for managed, even-aged stands of white or grand fir east of the Cascades in Oregon and Washington.** Res. Paper PNW-252. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 13 p.

Curtis, Robert O.; DeMars, Donald J.; Herman, Francis R. **Which dependent variable in site index-height-age regressions?** Forest Sci. 20(1):74-87; 1974 March.

Curtis, Robert O. **Growth and yield in uneven-aged stands.** In: Proceedings of an in-service workshop on uneven-aged silviculture and management in the western United States; 1976 October 19-21; Redding, CA. Washington, DC: U.S. Department of Agriculture, Forest Service; 1977: 81-97.

Dolph, K. Leroy. **Site index curves for young-growth incense-cedar of the westside Sierra Nevada.** Res. Note PSW-363. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 8 p.

Dunning, Duncan; Reineke, L. H. **Preliminary yield tables for second-growth stands in the California pine region.** Tech. Bull. 354. Washington, DC: U.S. Department of Agriculture; 1933: 24 p.

Husch, B. **Use of age at d.b.h. as a variable in the site index concept.** J. For. 54(5):340; 1956 May.

Monserud, Robert A. **Problems with site index: an opinionated review.** In: Bockheim. J., ed. Forest land classification: experiences, problems, perspectives: Proceedings of a symposium; Madison, WI: University of Wisconsin; 1984: 167-180.

Powers, Robert F.; Oliver, William W. **Site classification of ponderosa pine stands under stocking control in California.** Res. Paper PSW-128. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 9 p.

Schumacher, Francis X. **Yield, stand, and volume tables for white fir in the California pine region.** Bull. 407. Berkeley: California Agriculture Experiment Station, University of California; 1926. 26 p.

Stage, Albert R. **Prognosis model for stand development.** Res. Paper INT-137. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973. 32 p.

Spurr, Stephen Hopkins. **Forest inventory.** New York: Ronald Press; 1952: 476 p.

Tappeiner, John C., II. **Sierra Nevada mixed conifer.** In: Eyre, F. H., ed. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters; 1980:118-119.

GPO-786-673-79072

The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Dolph, K. Leroy. **Site index curves for young-growth California white fir on the western slopes of the Sierra Nevada.** Res. Paper PSW-185. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1987. 9 p.

Site index curves for young-growth California white fir were developed by using stem analysis data from 77 dominant and codominant trees growing in mixed-conifer stands on the western slopes of the Sierra Nevada. Site index reference age is 50 years at breast height. A family of 11 curves is presented for site index estimation. For more precise estimates, the site index estimating equation can be solved by using appropriate values of total tree height and breast-height age.

Retrieval Terms: site index, increment (height), stem analysis, white fir, *Abies concolor*, Sierra Nevada, California